LWRS Advanced LWR Nuclear Fuels

George Griffith
Light Water Reactor Sustainability (LWRS)
Advanced LWR Nuclear Fuel Pathway Lead

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www.inl.gov

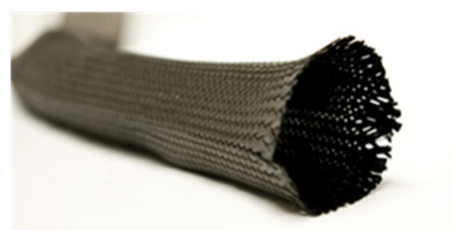
Idaho National Laboratory

Technology Drivers

- Advanced LWR nuclear fuel development
  - Nuclear fuel technology helps define safety margin at LWRs
  - Increased safety margin can be used to compensate for aging that is related to loss of safety margin
  - Reduced operating and economic risks
- Higher capability fuels allow for increased reactor economics
  - Improved economic optimization – fuel cycle length, power uprates, less used fuel, and more reliable fuel
- Improved understanding allows for shorter design and test cycles
  - Faster response to reactor needs
  - Improved fuel design process and better margin maintenance
- Technology demonstration can allow step improvement in fuel designs
  - Step improvement allowed by higher risk/reward design work

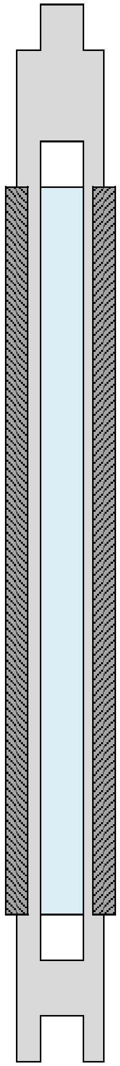
SiC Ceramic Matrix Composite (*CMC) Potential Benefits*

- SiC Clad – Application to Current LWRS Issue
  - Flagship approach to LWRS advanced nuclear fuels development
  - High-temperature strength and low chemical activity allows cladding to operate at very high temperatures
  - Allows longer service life and exposure
  - Thermal creep may not be an issue at operational temperatures
  - SiC fiber-reinforced composite may exhibit better mechanical characteristics for PCI
  - Use of SiC composite may mitigate flow-induced modes and subsequent fretting

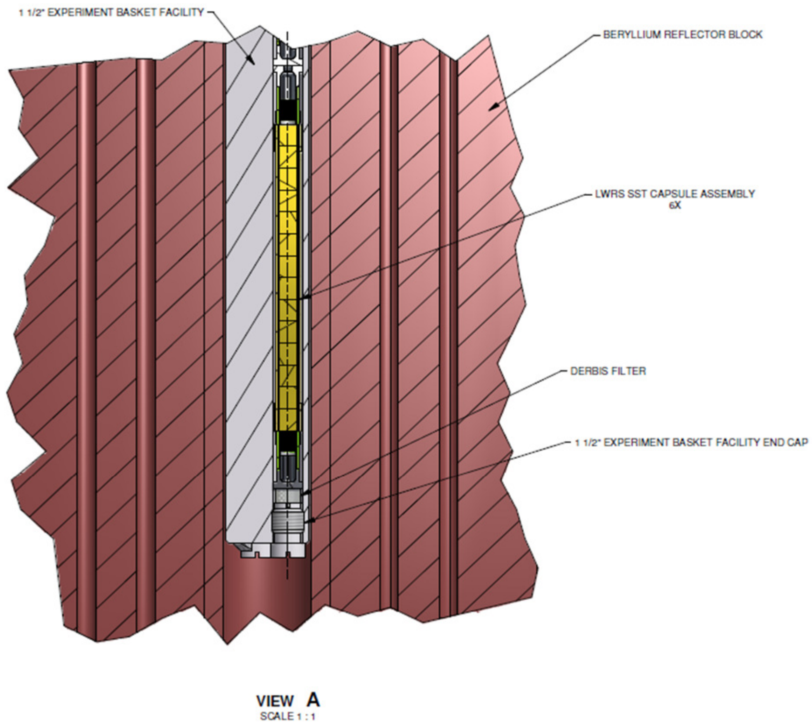


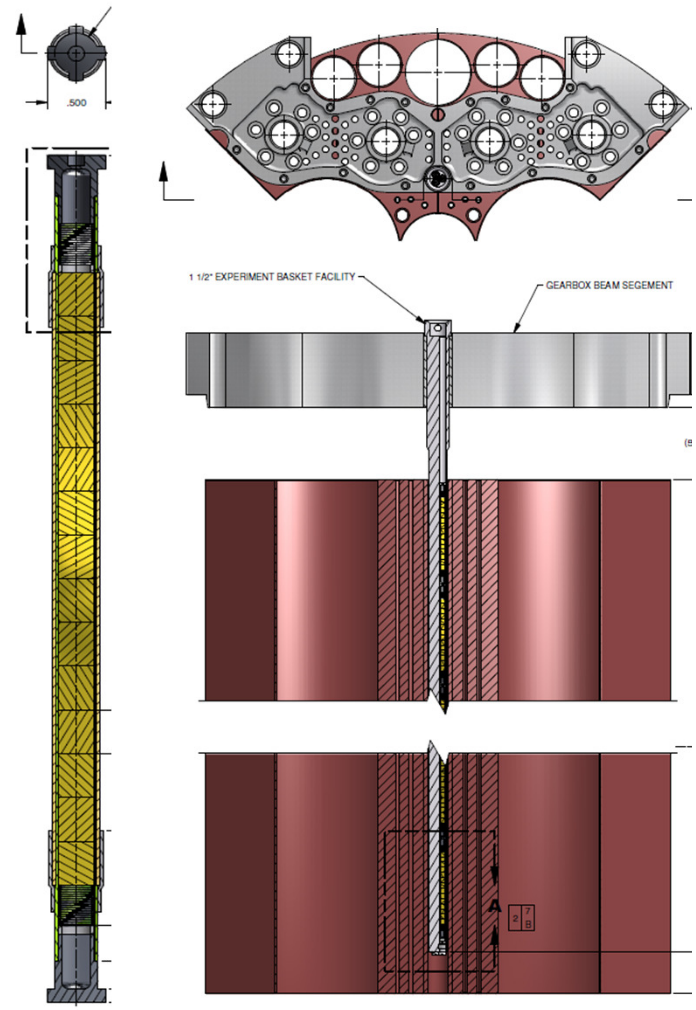
Irradiation Plan of SiC CMC Fuel Cladding

- Current irradiation in the high-flux isotope reactor (HFIR)
  - Testing full SiC CMC system
  - UO_2 and UN fuel
  - Short-term irradiations
  - MITRR pressurized water reactor flow-loop testing
- ATR irradiations
  - SiC CMC/metal hybrid system
  - Steady state
  - Power ramp testing
  - Pressurized water reactor flow loop
- Halden Reactor Project
  - Severe power ramps
  - Instrumented irradiation
    - Pressure, temperature, and stresses
  - Failure mode testing

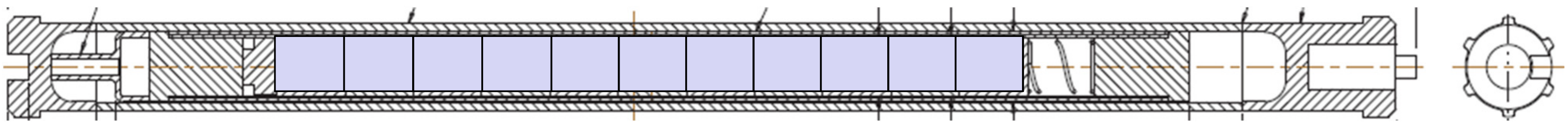


ATR SiC CMC Experimental Test Arrangement

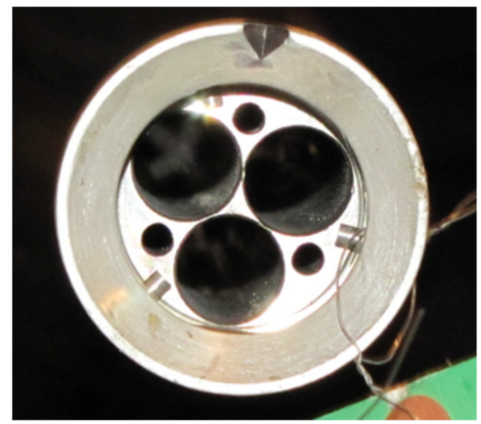




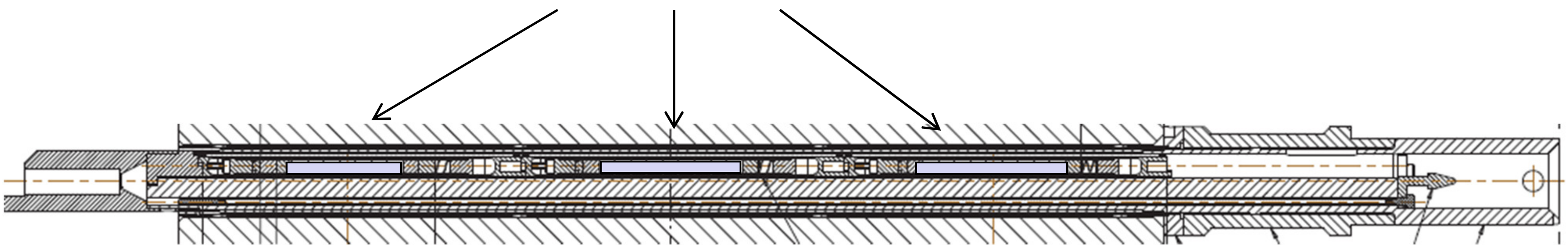
HFIR SiC CMC Experimental Test Arrangement



Irradiation of UO_2 and UN-fueled SiC CMC rodlets ongoing at HFIR



fueled rodlets



LWR Cladding Outside Surface Nanometer-Scale Coating for Corrosion and Crud Control

Haiyan Wang Texas A&M University

- Create zirconium cladding that is less susceptible to fretting failures and hydrogen reactions than conventional cladding
- Lower risk technology than fuel SiC cladding technology

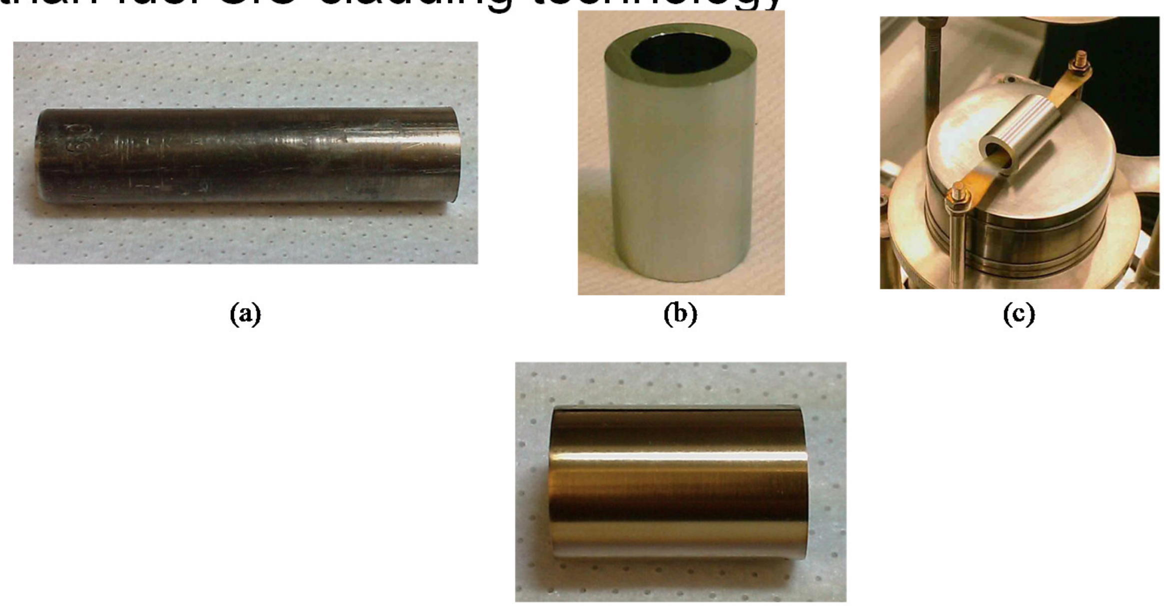
Zircaloy-4 tube for TiN coating

(a) Before polishing

(b) Cut and polished

(c) Mounted zircaloy-4 tube on heater of PLD chamber

(d) TiN-coated tube.

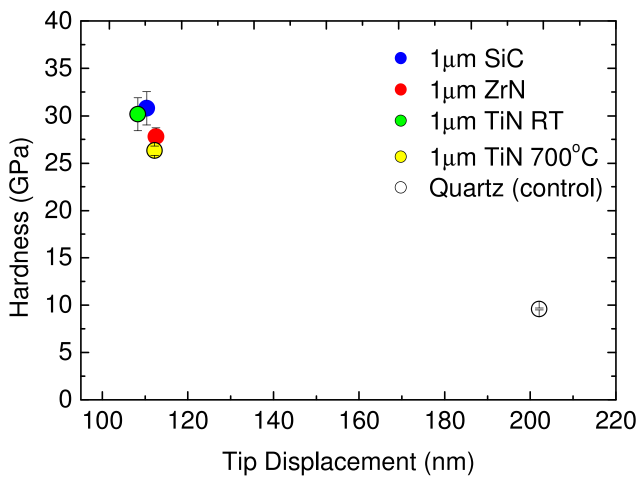


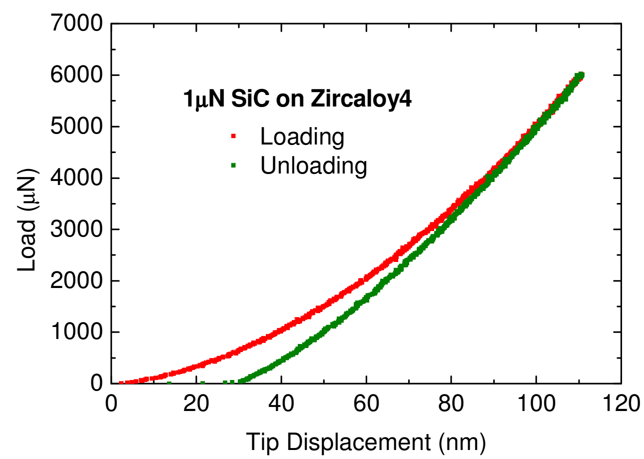
(a) (b) (c)

(d)

LWR Cladding Outside Surface Nanometer-Scale Coating for Corrosion and Crud Control

Haiyan Wang Texas A&M University





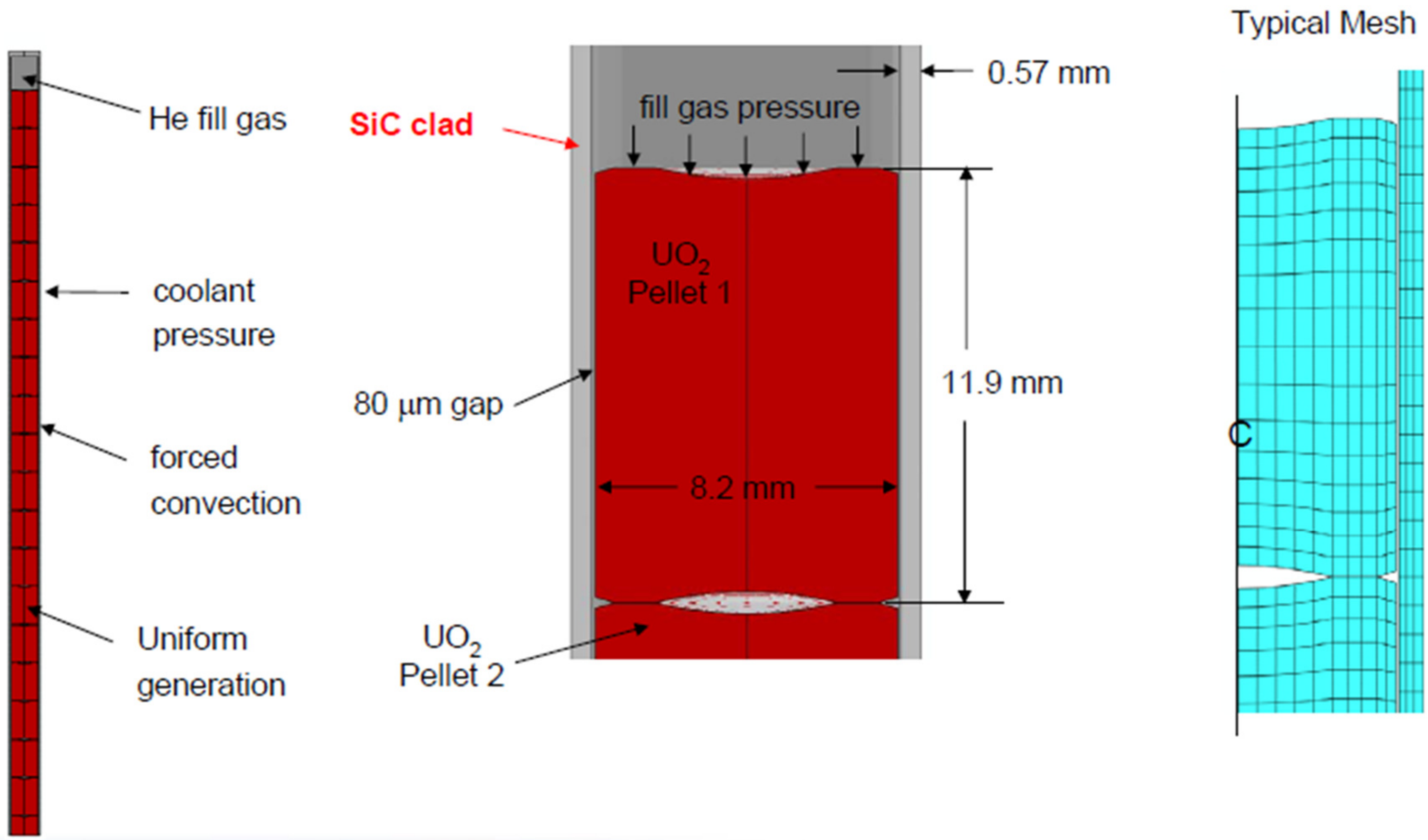
•Hardness of 500°C SiC and ZrN, room temperature TiN, and 700°C TiN on zircaloy-4 substrates.

•All show high hardness consistency

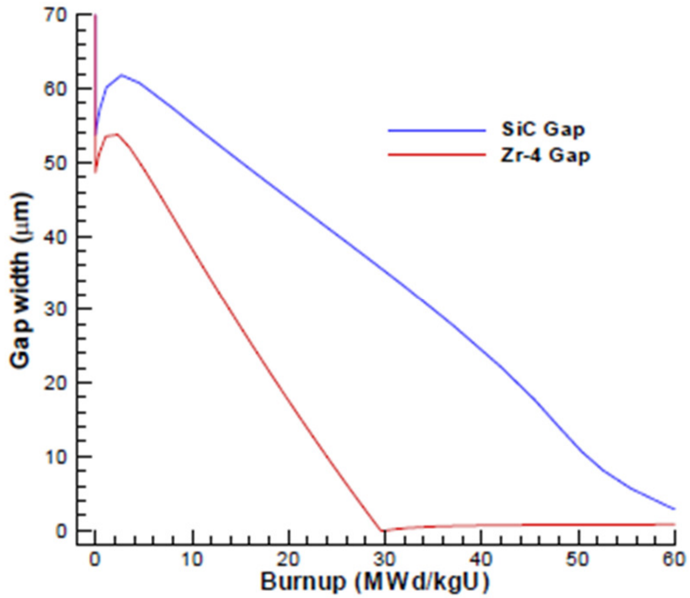
Provide commercial cladding for coating and irradiation

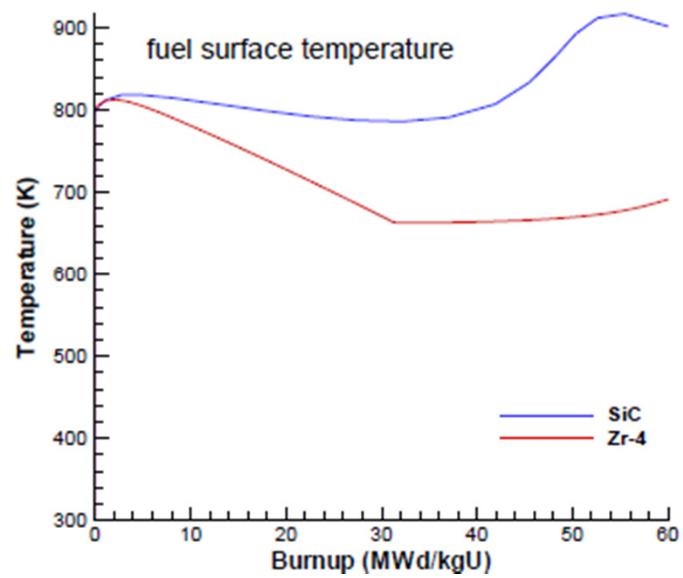
Modeling Activities

20 Pellet Axisymmetric Fuel Rod Model



Comparison of Zircaloy-4 and SiC Clad Material Performance

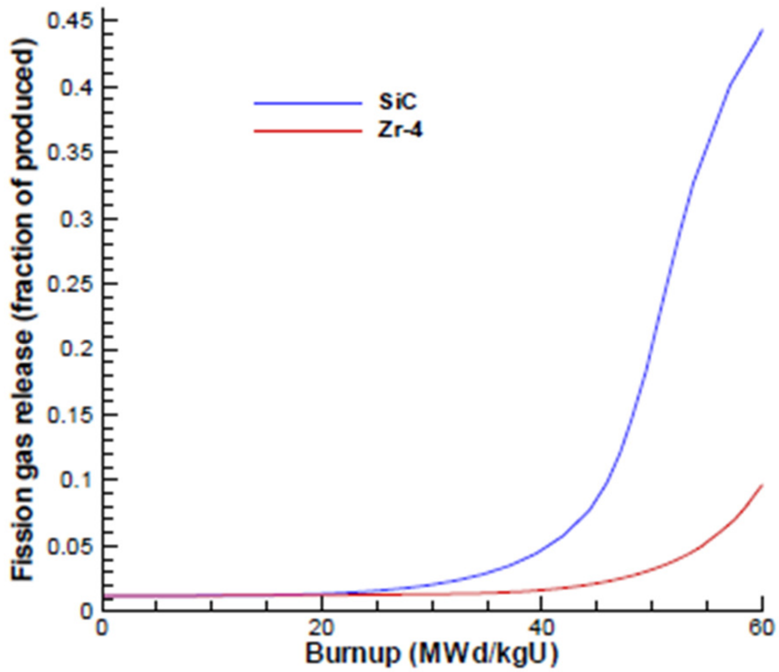


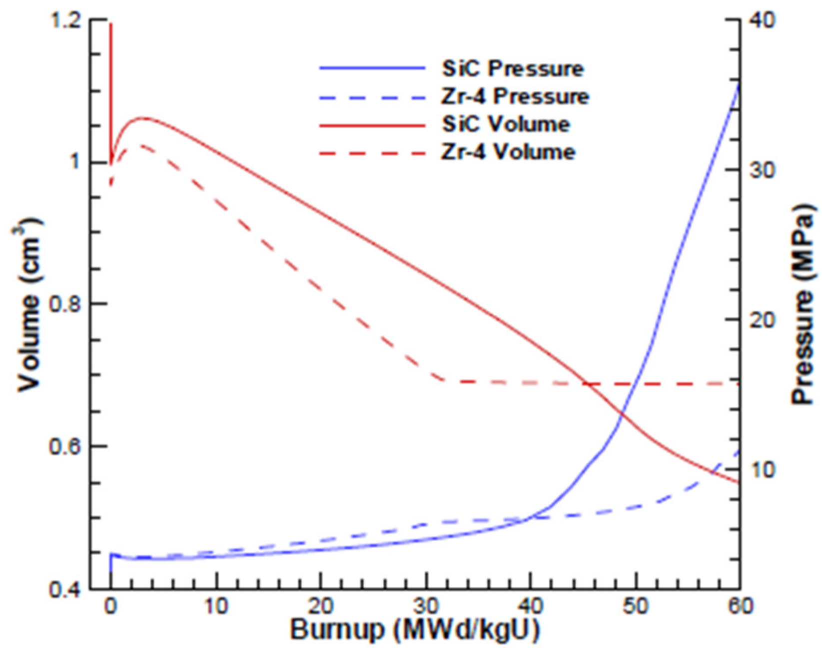


•Lack of SiC clad creep down results in a significantly lower gap closure rate and no PCI at 60 MWd/kgU

•Larger fuel-clad gaps result in higher fuel temperatures, particularly late in the fuel life when large amounts of low conductivity fission gases fill the gap

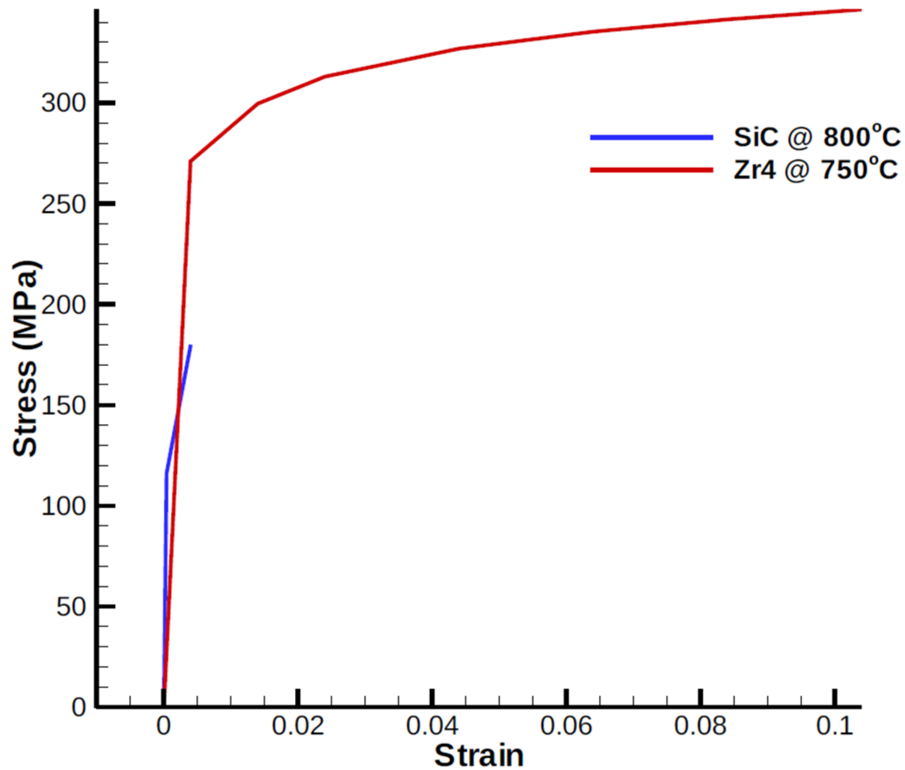
Comparison of Zircaloy-4 and SiC Cladding Material Performance



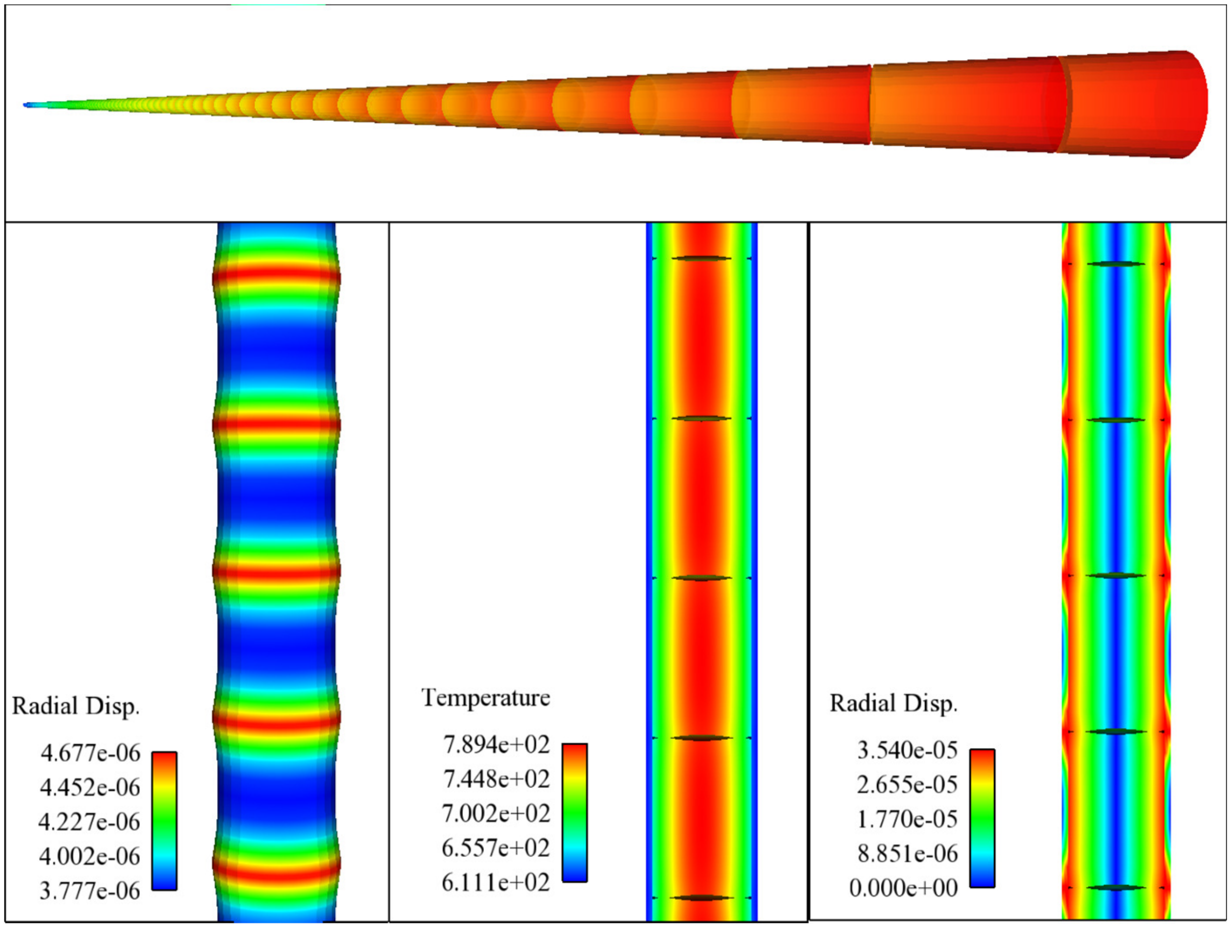


- Higher fuel temperatures result in more fission gas release and higher gap/plenum pressures late in fuel life
- Clad material appears to have a substantial effect on fuel rod performance

Comparison of Zircaloy-4 and SiC Cladding Material Performance



Modeling Activities



Results from a 100-pellet fuel rod simulation

PCI Modeling

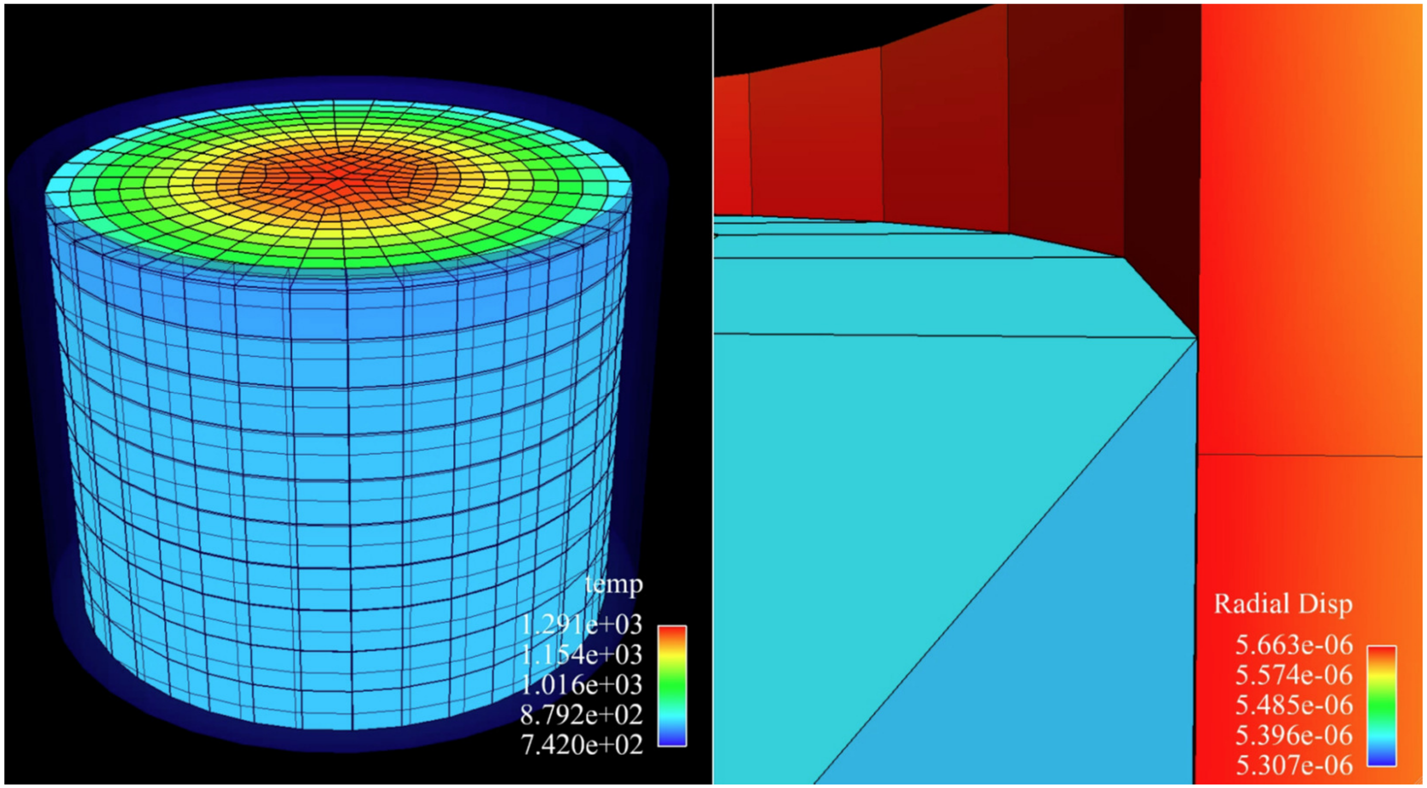
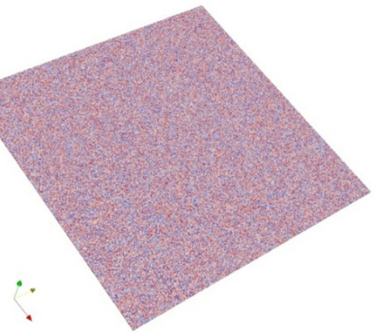
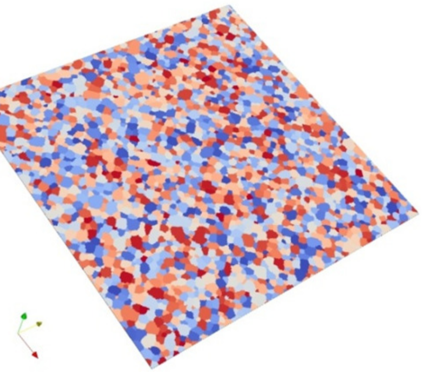
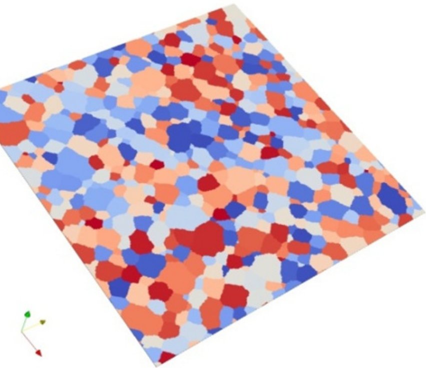


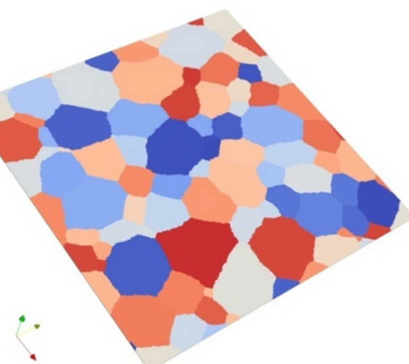
Diagram of a single pellet interacting with the cladding

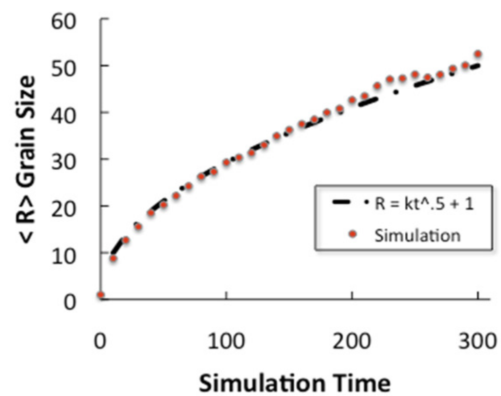
Kinetic Monte Carlo Potts Grain Growth Simulation





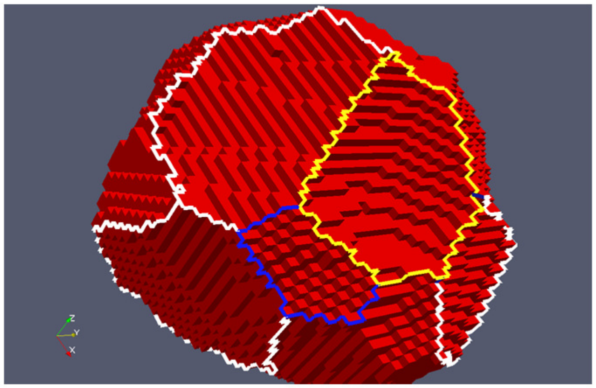






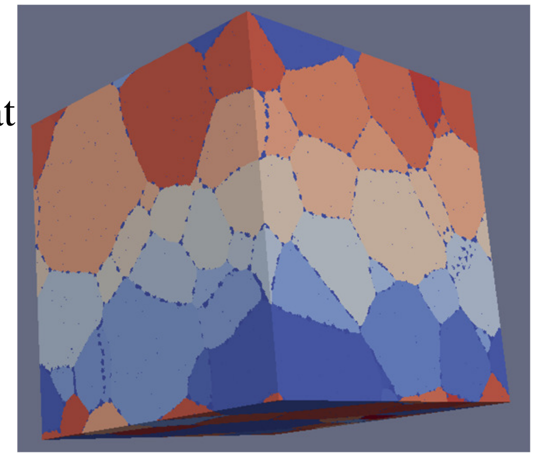
Energy differences at boundary drive the system to larger crystals

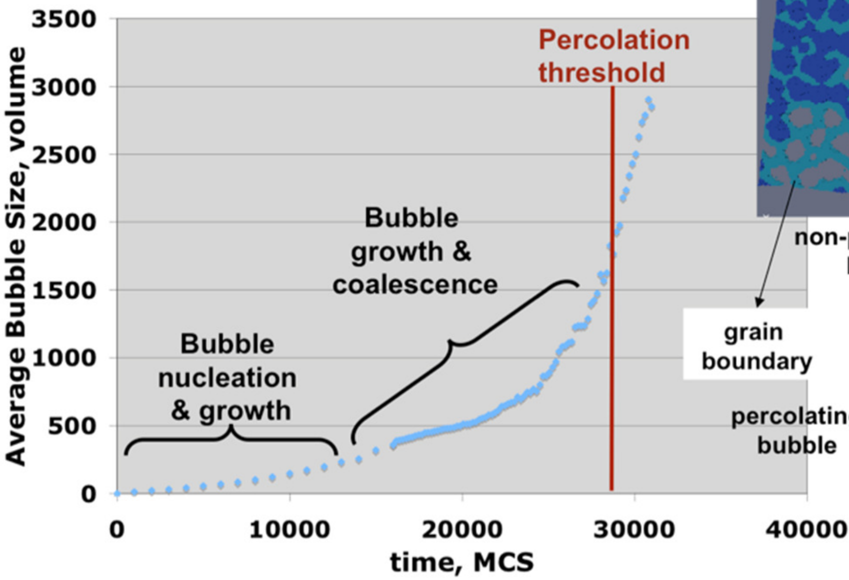
Kinetic Monte Carlo Potts Grain Growth Simulation

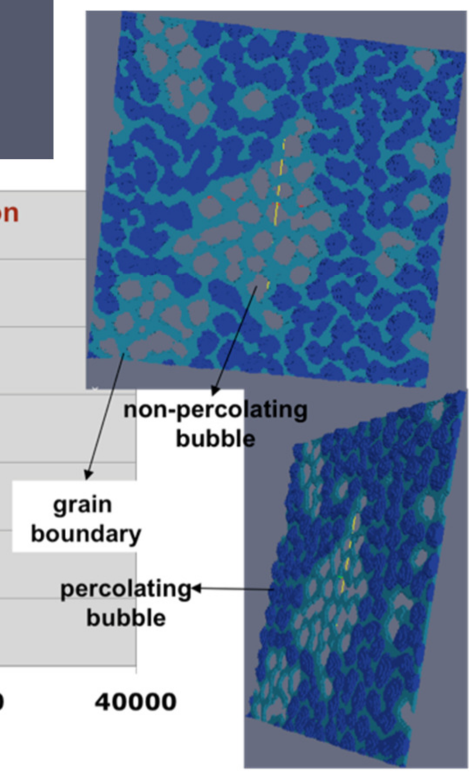


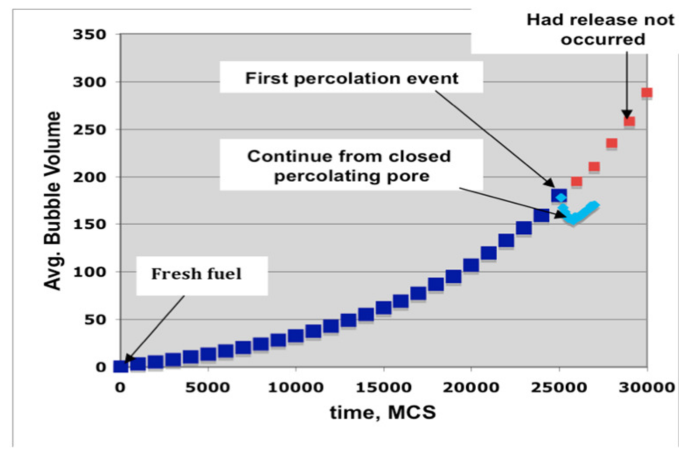
Three-dimensional crystal

Helium bubble growth at crystal boundary



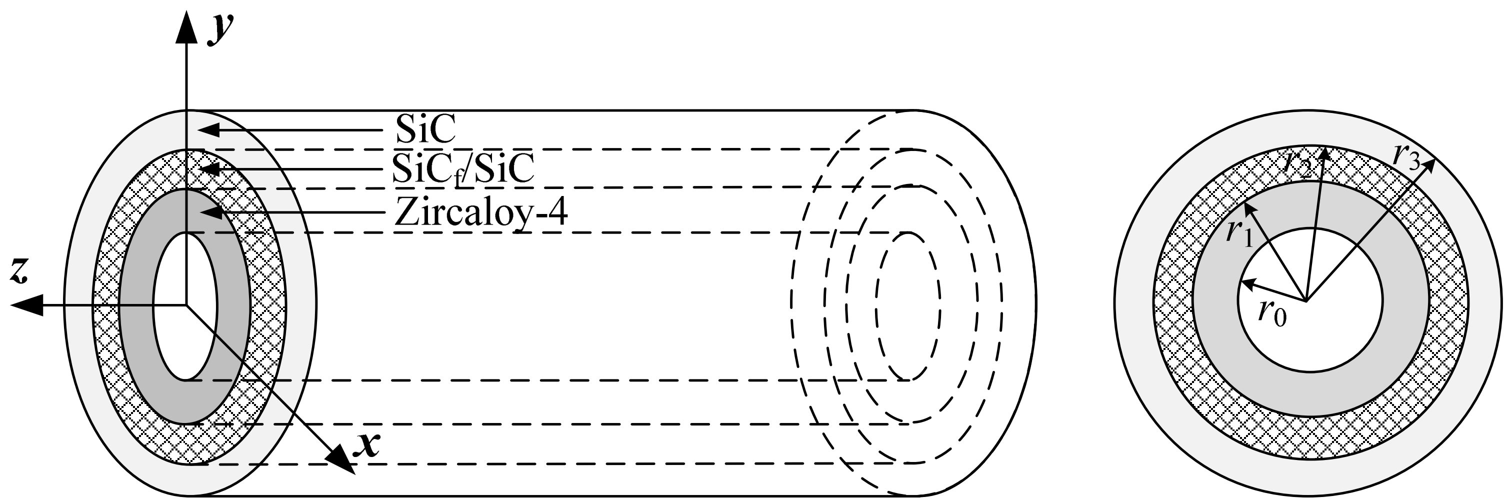






Energy differences at boundary drive the system to larger crystals

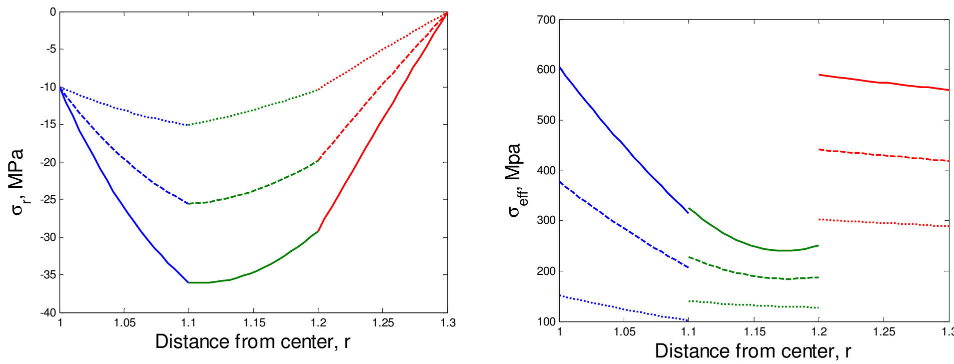
Mechanical Problem Illustration



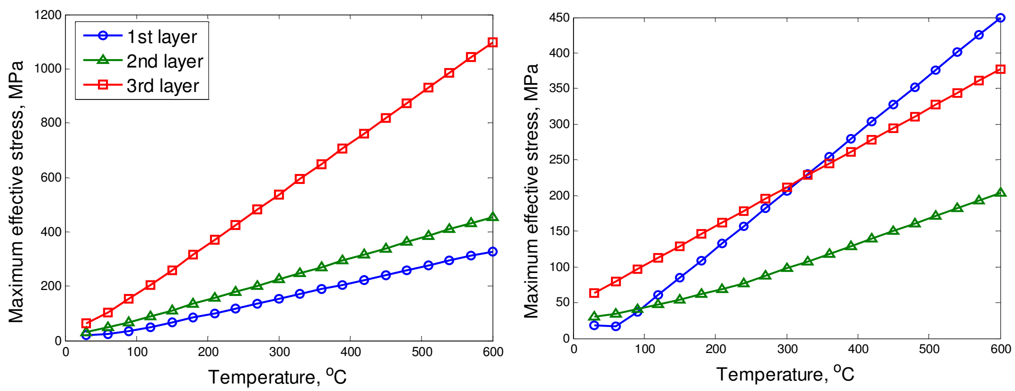
Schematic of the three-layer cladding tube under consideration. The three layers are (1) the inner layer (zircaloy-4), providing the hermetic seal; (2) the core layer (SiC_f/SiC composite), improving the load-carrying capacity; and (3) the outer layer (beta phase SiC), enhancing the strength.

The tube is subjected to thermo-mechanical loads, including internal pressure, external pressure, axial strain, and temperature gradient. However, the influence of irradiation on material properties is not considered in the current study.

Numerical Results and Discussion



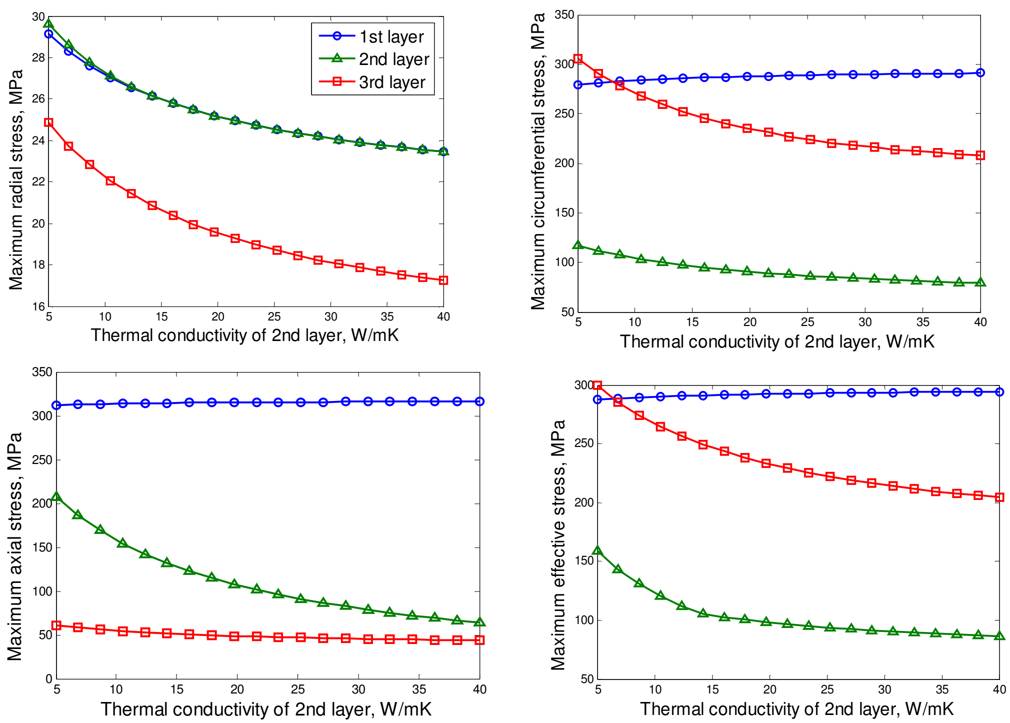
Stresses in the tube wall under various thermal loads: $T_i = 200$ (dotted line), 400 (dashed line), and 600ºC (solid line), with T_o fixed at 100°C.



Maximum effective stress in each layer varying with the temperature T_i on the inner surface: (a) uniform temperature distribution with $T_o = T_i$ and (b) steady-state heat flow with T_o fixed at 25°C.

- ❑ Under pure thermal loads, maximum stress is found to be located at the bonding interfaces and increases with T_i .
- ❑ Thermal loads under condition (a) are significantly smaller than under condition (b).

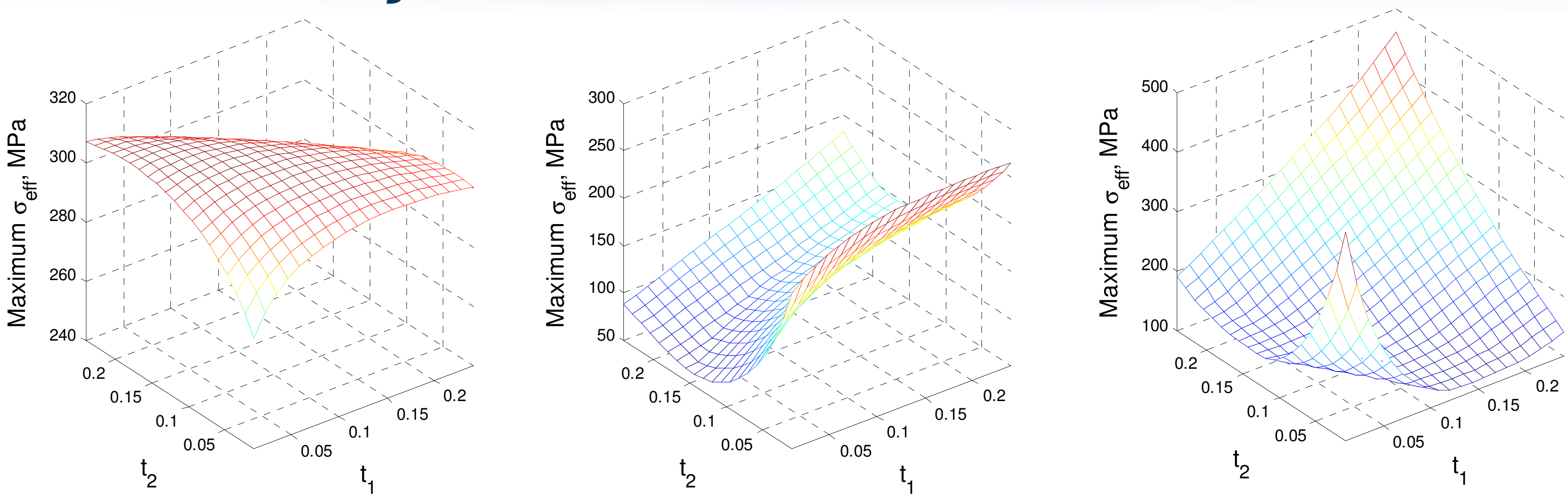
Numerical Results and Discussion



Maximum values of the stress components and effective stress, varying with the thermal conductivity of the SiC_f/SiC layer.

- ❑ The maximum radial stress in all three layers decreases with increasing $k_{rr}^{(2)}$ with the reduction slowing down as $k_{rr}^{(2)}$ gets larger.
- ❑ The reduction in σ_{eff}^{max} is more significant when $k_{rr}^{(2)}$ is below 15 W/mK. Therefore, for the current ZRY4-SiC_f/SiC-SiC composite tube, it is not necessary to use a SiC_f/SiC composite with a thermal conductivity higher than 15 W/mK.

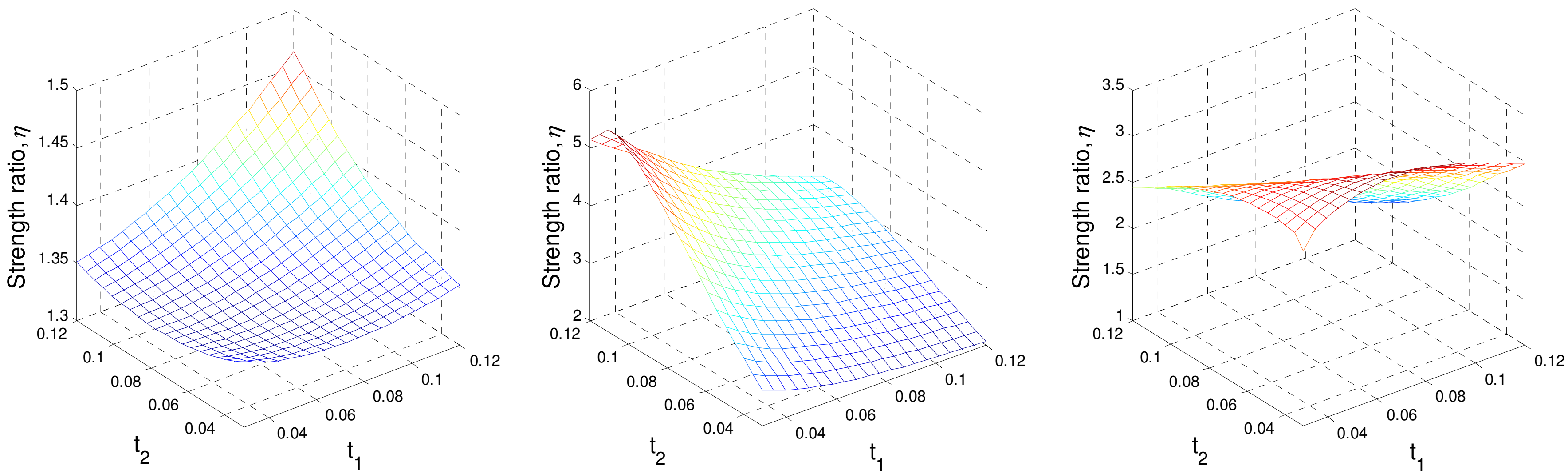
Effect of Layer Thickness



Effect of layer thickness on the maximum effective stress in (a) the zircaloy-4 layer, (b) the SiC_f/SiC layer and (c) the SiC layer. Here t_1 and t_2 denote the zircaloy-4 layer thickness and the SiC_f/SiC layer thickness, respectively.

- ❑ The influence of changing t_1 and t_2 on σ_{eff}^{max} in the zircaloy-4 layer is small when compared to that in the SiC_f/SiC and SiC layers.
- ❑ In the SiC_f/SiC layer, small values of t_1 lead to small values of σ_{eff}^{max}, while very small values of t_2 result in large values of σ_{eff}^{max}. A value of t_2 around $0.15r_0$ corresponds to the smallest σ_{eff}^{max} for a given t_1.
- ❑ Increasing t_1 or t_2 tends to increase σ_{eff}^{max} in the SiC layer, thereby reducing the margin of safety of this layer.

Optimization Results



Effect of layer thickness on the safety factor of (a) the zircaloy-4 layer, (b) the SiC_f/SiC layer, and (c) the SiC layer.

- The SiC_f/SiC layer has the largest value of η and the zircaloy-4 layer the smallest, which implies that the zircaloy-4 (inner) layer is most vulnerable under current operating conditions.
- Increasing t_1 or t_2 enlarges the value of η in the zircaloy-4 layer but reduces it in the SiC layer.
- An optimal value of $\eta = 1.45$ is obtained by setting $t_1 = t_2 = 0.12r_0$ and $t_3 = 0.6r_0$.

Results

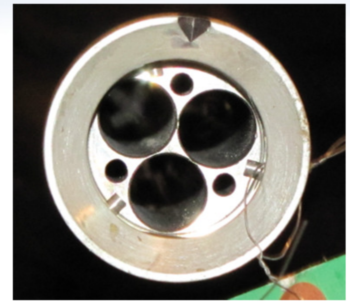
- Stresses induced by thermal loads can be much larger than those caused by mechanical loads.
- The radial stress value is one order of magnitude smaller than that of the circumferential stress or axial stress.
- The maximum values of the stress components in each layer exist at the bonding interfaces under pure thermal loads.
- Increasing the thermal conductivity of the SiC_f/SiC composite layer improves the tube performance by reducing the maximum effective stress.
- When the conductivity value goes above 15 W/mK, minimum improvements in thermal stress are observed.
- In the three-layer tube studied, the SiC CMC core layer has the highest safety factor when the zircaloy-4 layer is thinnest.
- An optimal design with a maximized safety factor for the three-layer tube can be achieved by adjusting the thicknesses of two or three layers.

LWRS Advanced Nuclear Fuel Pathway Status

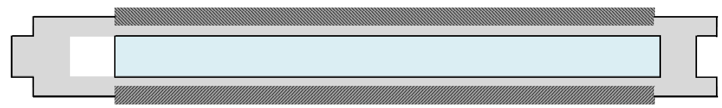
- Commercial prototype SiC cladding is being irradiated at the Oak Ridge HFIR reactor
- Fabrication of advanced SiC/metallic hybrid cladding is ongoing
- ATR irradiation plans are on schedule for the second quarter of FY 2011
- Thin ceramic films have been applied to zirconium samples
- Advanced modeling is providing design inputs
- Mechanical modeling has started
- A shared technology project on SiC reactor structures is being developed

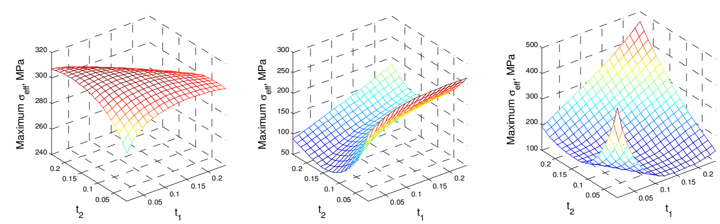
SiC CMC Advanced LWR Cladding

INL Program: LWRS, Fuel Cycle Research and Development
INL Investigator: George Griffith



- Project Goal: Create and demonstrate high-performance LWR nuclear fuel to support the LWR life-extension program
- Sample Types: SiC CMC nuclear fuel cladding and SiC CMC/metallic hybrid fuel rodlets
- Prototype rodlets are being fabricated for fueled experiments at ATR, HFIR, and the Halden Reactor Project; support for prototype SiC CMC-fueled HFIR irradiations
- Samples in first cycle at HFIR
- 2011 ATR irradiations





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CASL

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NEAMS

ATR National Scientific User Facility